Raised Marine Terrace on North-west Coast of Macquarie Island

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Bathymetric data off the north-west coast of Macquarie Island shows a wide, gently sloping marine terrace extending offshore for up to 4600m. The submerged terrace is an extension, without change of average slope, of the onshore terrace. We consider that the whole terrace was formed during the period of rapid rise in sea-level following the last world-wide glacial maximum of the terminal Pleistocene. During the period from about 16 000 to 8000 years ago the combination of vigorous erosive action by the Southern Ocean, the fractured bedrock and the rise in sea-level accounts for retreat of the cliffs bounding the western edge of the island's plateau at an average of c.0.5m per year. Since world-wide sea level stabilized, continuing tectonic uplift at approximately 3mm per year has lifted the landward third of the terrace above sea-level.

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INTRODUCTION

Subantarctic Macquarie Island, 54°S 159°E, is an above-sea portion of the tectonically active Macquarie Ridge. Macquarie Island is uplifted oceanic crust from the eastern margin of the Australian plate (Williamson, 1988). Differential movement between the Australian and the Pacific plate is the source of the moderately high seismic activity along the Ridge (Jones and McCue, 1988).

Recognition of cobble and pebble beaches of marine origin, now raised significantly above sea-level (Varne, Gee and Quilty, 1969; Ledingham and Peterson, 1984) indicate that uplift of the island's surface above sea-level is relatively recent. Evidence from a variety of sources has allowed calculation of uplift rates for various parts of the island.

Studies of peat and penguin bones (McEvey and Vestjens, 1973) allowed Colhoun and Goede (1973) to calculate a maximum rate of 4.5mm per year and a minimum rate of 1.5mm per year, for beach terrace uplift at Bauer Bay and Green Gorge. Bergstrom's (1985) studies of peats in the Green Gorge basin allowed calculation (Selkirk, Seppelt and Selkirk, 1990) of uplift rates of 2mm and 5mm per year. From the height of the landward edge of the rock-cut marine terrace north of Bauer Bay, and assuming approximate stability of sea-level for the last c.6000 years, Adamson, Selkirk and Colhoun (1988) calculated uplift rates between 1.7 and 3.3 m per year.

The island is composed of a number of blocks likely to have moved vertically, or to have tilted, at different rates and to different extents relative to each other during the overall uplift process. A north-west-trending fault crosses the isthmus — separating Wireless Hill from the rest of the island. From studies of a peat deposit overlying a raised beach, Selkirk, Selkirk and Griffin (1983) calculated an uplift rate of 14.5mm per year for a Wireless Hill site. Bye (1988), using data from tide gauge measurements in Buckles Bay, calculated an apparent rate of uplift of the tidal datum of between 6 and 13mm per year, commenting that this is of the same order of magnitude as the uplift rate calculated for nearby Wireless Hill.

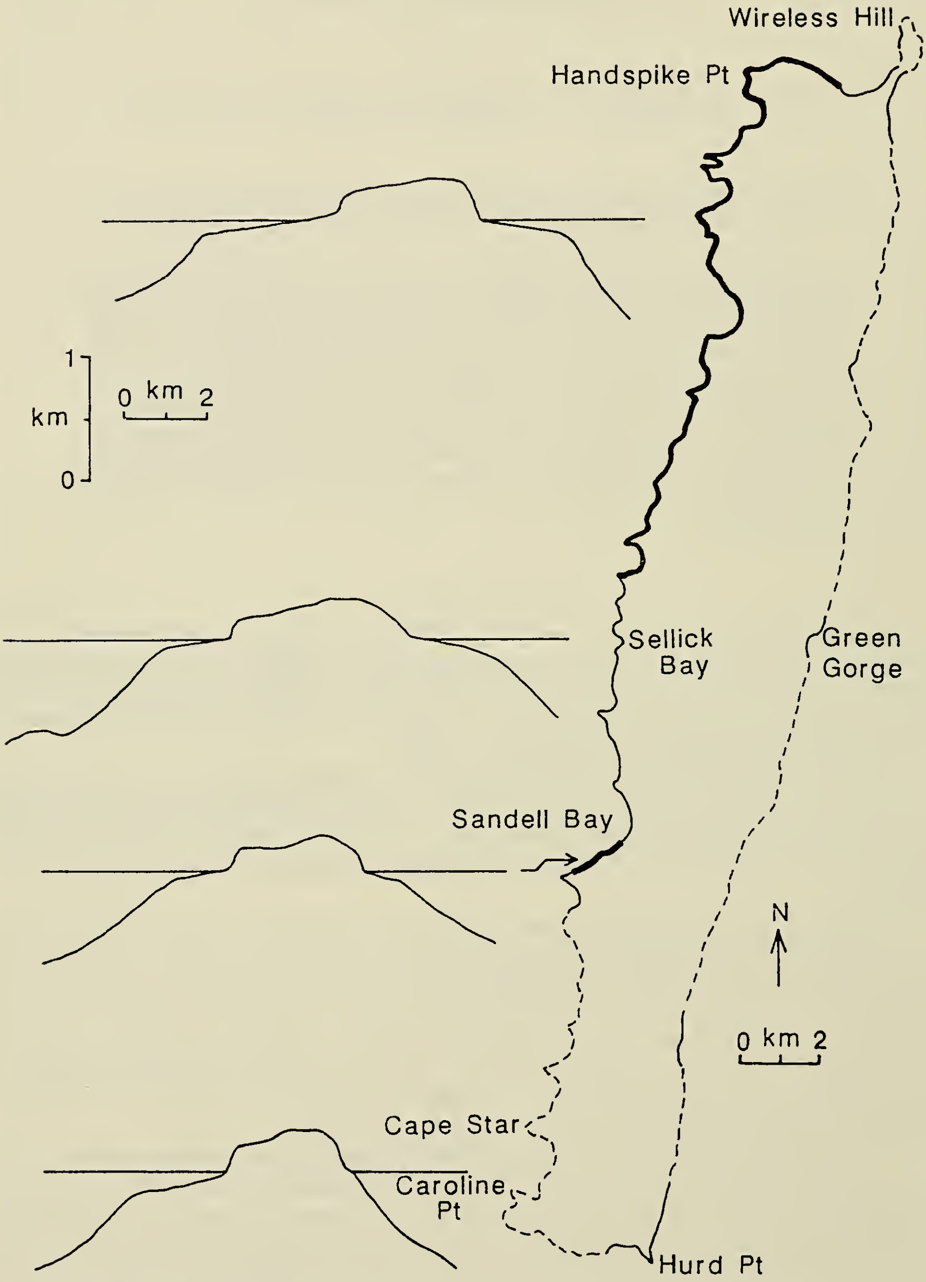

Fig. 1. (a) The coastline of Macquarie Island divided into three categories: wide marine terrace (thick line), medium width marine terrace (thin line), narrow or no marine terrace (dashed line). Terrace width is variable from bays to headlands, and although precise values for the width categories are difficult to allocate, in general a wide terrace would be several hundreds of metres and a narrow terrace would be less than 50 m in width. (b) Four east-west sections of the island and adjacent ocean floor.

Wide Marine Terrace

At the north-west corner of the island, and extending along the northern half of the west coast, a wide, gently sloping terrace extends from the shoreline to about 15 to 20m a.s.l., terminating at the base of the cliffs which bound the plateau (Fig. 1). Here the terrace is several hundred metres wide (Fig. 2, 3, Table 1). Other parts of the coast are bounded by a narrower terrace of similar form (Fig. 1, 4) or by cliffs which plunge directly into the ocean (Fig. 1, 5).

Fig. 2. Wide marine terrace at Half Moon Bay, photographed from plateau above Handspike Corner, looking southwards to Elizabeth and Mary Point, Eagle Point, Unity Point and Langdon Point. Plateau on left is approx. 200m a.s.l.

Fig. 3. Bauer Bay, photographed from plateau edge, retains sand carried from the plateau by Bauer Creek (bottom right of photograph). Washed rock surface of the wide marine terrace between Bauer Bay and Douglas Point (top right of photograph) is partly mantled by mire vegetation and ponds. Rock stacks rise above the average slope of the terrace).

Adamson, Selkirk and Colhoun (1988) described the nature of the surface of the terrace near Bauer Bay. They proposed that the terrace had been cut during a period of severe marine erosion of coastal cliffs between c.16 000 and c.8000 BP when world-wide sea-level was rising faster than uplift of the island. During the period of substantially stable sea-levels since c.6000 BP the terrace has progressively emerged from the sea as uplift of the island has continued. From their hypothesis for the terrace's formation, Adamson, Selkirk and Colhoun (1988) presented a model which predicted that the terrace extends undersea offshore to a total width of 1000 to 3000m, with the seaward edge of the terrace now 70 to 100m below present sea-level. This paper presents evidence from offshore to test these predictions.

Nearshore Bathymetry

Published bathymetric data for the area adjacent to the island are few (British Admiralty Chart No. 1022; Mawson, 1943). From these it seems that the seafloor slopes away from the island more steeply to the east than to the west, but nearshore configuration of the sea floor immediately to the west of the island was not known. Profiles across the Macquarie Ridge (Mawson, 1943) showing a shelf gently sloping for approximately 6km to the west of the island before a change to a steeper slope are, in the western portion, conjectural. 'Soundings off the west coast, except at the north end, are not sufficiently numerous to obtain a clear picture of the bottom contour adjacent to the Island. The soundings taken on that side of the Island do, however, demonstrate that . . . shallow water extends over a wide area' (Mawson, 1943).

TABLE 1

Measured and calculated parameters for 5 traverses across submerged marine terrace, north-west coast of Macquarie Island. Traverse locations shown on Fig. 6, profiles in Fig. 7

Traverse no.	Bearing (°)	Offshore width (m)	Depth of offshore edge (m)	Underwater slope	Onshore width (m)	Total width (m)
1	270	2100	70	1.9	600	2800
2	281	1400	90	3.7	500	1900
3	295	2500	100	2.3	1100	3600
4	305	4000	100	1.4	700	4700
5	339	4600	90	1.1	900	5500

From these 5 traverses, average offshore width = 2920m, average depth of offshore edge = 90 m, average underwater slope = 2.1°, average total width = 3700m.

Bathymetric data available to December 1970 were compiled by the Antarctic Mapping Branch, Division of National Mapping into a manuscript map. Additional bathymetric data for the vicinity of Macquarie Island, including to within 1.5km of its north-west coast, became available as a result of a Bathymetric Survey Program from MV 'Cape Pillar' in January 1982 (Manuscript Bathymetric Map, Division of National Mapping, 1982). Profiles across the island and the nearshore seafloor (Fig. 1) and a bathymetric map for the surrounds of the northern third of the island have been constructed from these sources (Fig. 6).

Testing the Terrace Formation Model

In order to test the predictions of Adamson, Selkirk and Colhoun's (1988) model, depth to the seafloor was determined along five traverses between Handspike Corner

Fig. 4. Medium width marine terrace at Hurd Point, looking east and showing uniform gentle seaward slope and emergent rock stacks.

Fig. 5. Coast at Cape Star with no terrace but rock stacks emerging from the ocean. Looking northwards from above Caroline Cove hut.

and Bauer Bay (Fig. 6) and across the course of MV 'Cape Pillar'. Depth soundings were taken from an amphibious vehicle (LARC) whose positions were plotted from compass sightings by three observers, one each at Handspike Point, Langdon Point and Mawson Point. Radio contact was maintained between LARCs and observers. The courses

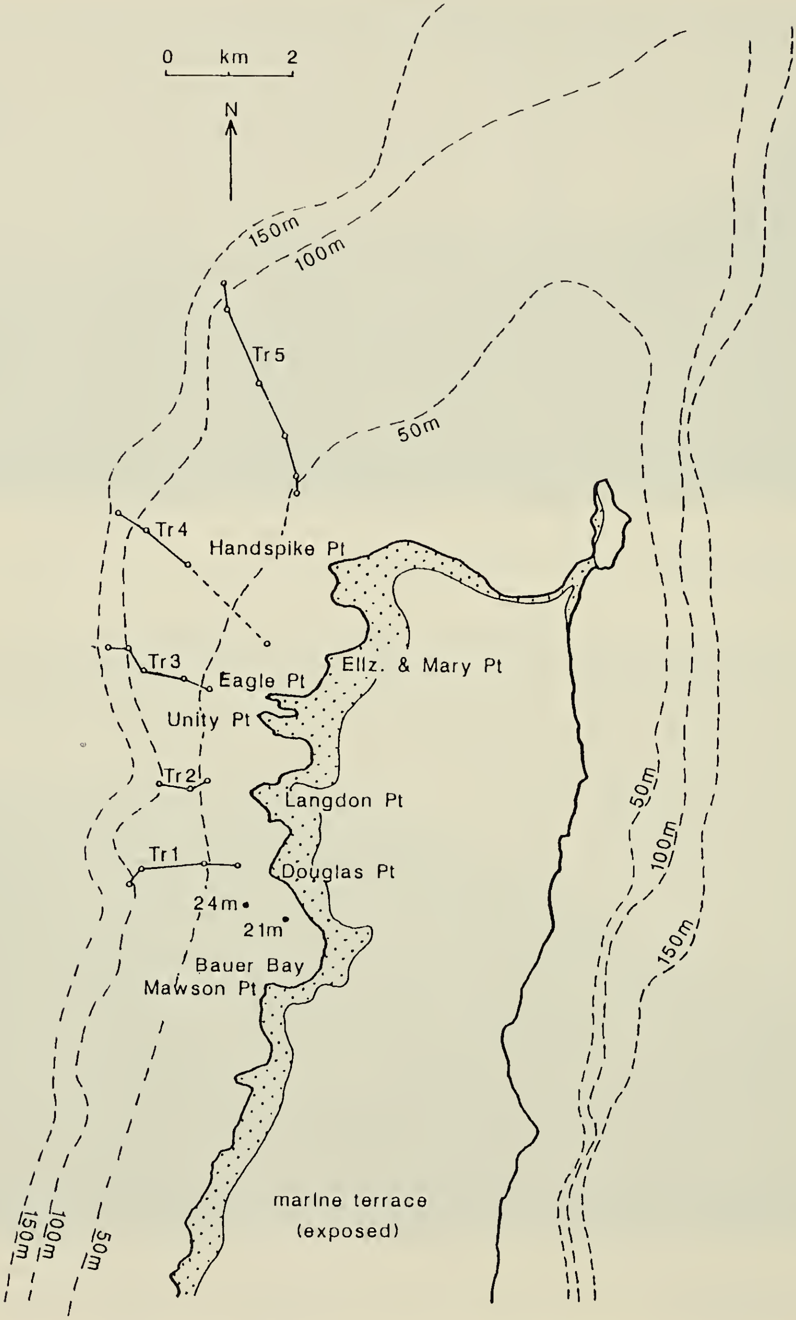

Fig. 6. Location of five LARC traverses, and approximate location of 50, 100 and 150m ocean depth contours around Macquarie Island. Marine terrace above present sea-level is stippled. Ocean soundings used to draw contours were obtained from an unpublished National Mapping compilation of soundings to 1970 and from MV 'Cape Pillar' soundings 1977, both charts held at the Australian Navy Hydrographic Office, North Sydney, NSW.

plotted are somewhat in error due to the difficulty of sighting accurately on a small craft in the heavy swell off the west coast, and the acknowledged shortcomings of the published 1:50 000 topographic map of the island used as the base for our maps (Berkery and Pritchard, 1987; Division of National Mapping, 1971). The errors do not affect the overall picture obtained.

Profiles along the traverses (Fig. 7) have been constructed, using a combination of these new data and that from the manuscript bathymetry charts. They show that the terrace slopes gently offshore to the west and north-west for between 1400 and 4600m. A distinct change of slope, at between 70 and 100m depth, marks the present seaward edge of the terrace. These measurements allow calculation of an overall slope of between 1 and 4° for the undersea part of the terrace (Table 1), comparing satisfactorily with Adamson, Selkirk and Colhoun's (1988) measured 1.5 to 4° slope for the onshore part of the terrace north of Bauer Bay.

Discussion

Profiles drawn across the northern part of the island from existing maps and data collected during the LARC traverses reported here show that the island is flanked to the west by a gently sloping platform at present partly above and partly below sea-level (Fig. 1, 3). The overall slope of the platform (1 to 4°), its total width (2000 to 5500m) and the depth of its westward margin below present sea-level (70 to 100m) are all consistent with predictions from the model proposed for formation of the raised marine platform (Adamson, Selkirk and Colhoun, 1988). This model is based on the known world-wide rise in sea-level following the last glacial maximum at c.18 000 years ago, and on tectonic uplift of the island. Between c.16 000 and c.8000 years ago sea-level appears to have risen faster than tectonic uplift so that wave action caused vigorous erosion of the coastal cliffs, leaving a sloping platform as rising sea-level allowed waves to reach successively higher parts of the coast, and causing cliff retreat equalling the width of the platform, (Fig. 9).

The maximum depth of the seaward edge of the submerged marine terrace is about 70 to 100m below present sea-level. The height of the landward edge of the exposed terrace is 15 to 20m above present sea-level, making a total height difference between seaward and landward edges of between 90 and 120m. This lies within estimates of global sea-level rise following the last glacial maximum period, and is consistent with our inference that the whole terrace formed during this period of rapidly rising sea-level.

Palaeolake deposits at the top of these cliffs (Fig. 8) are remnants of lakes which formerly occupied parts of the plateau lost during cliff retreat and terrace formation (Fig. 9). The ages of the uppermost layers of these deposits represent the approximate date of lake drainage, and provide an independent means of dating the formation of the cliff line between the terrace and the western plateau margin. Dates of 8620 ± 170 radiocarbon years (calibrated to 9420 ± 320 BP; Beta-20166) for a layer 220cm below the present surface vegetation at Palaeolake Skua, and of 5220 ± 80 radiocarbon years (calibrated to 6025 ± 290 BP; Beta-20164) for a layer 160cm below the present surface vegetation at Palaeolake Sandell (Selkirk *et al.*, 1988) are consistent with our interpretation that the cliff line had retreated to its present position by about 6000 years ago.

The erosive effectiveness of wave action on sea cliffs depends on wave size and energy, coastal seafloor morphology, and cliff lithology and structure. Macquarie Island lies in the latitudinal zone of maximal occurrence of gale force winds throughout the year in the Southern Hemisphere (Davies, 1980), and just to the east of the zone of maximum high-latitude cyclogenesis (Adamson, Whetton and Selkirk, 1988). This storm belt of the Southern Ocean is probably the most important area in the world for generating

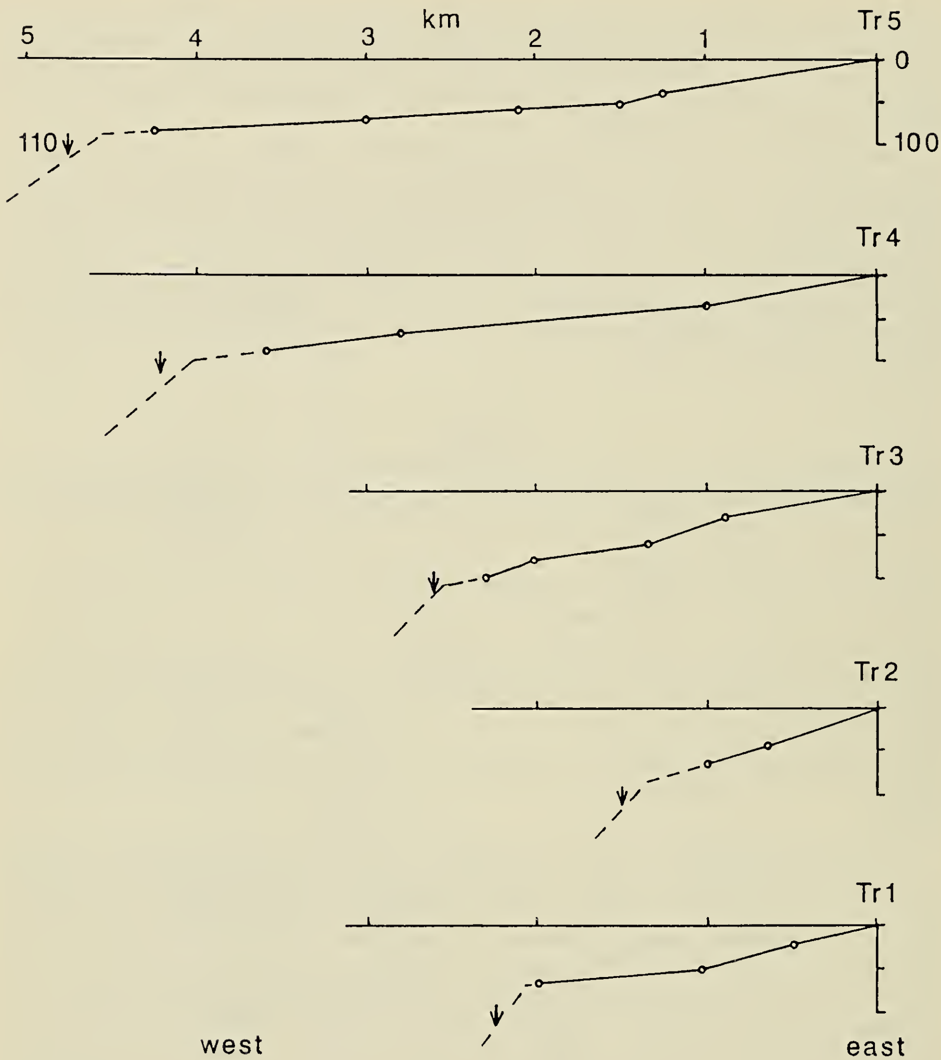

Fig. 7. Ocean depth along five LARC traverses off north-west coast of Macquarie Island. Location of traverses shown on Fig. 6. Open circles: spot depths from LARC. Arrow: depth measured from LARC greater than 110m (limit of depth sounder). Dashed line shows inferred break of slope at seaward edge of marine terrace.

swell and storm waves (Davies, 1980). At present on Macquarie Island there are about 6 days per month when average daily wind speed is gale force (17.5m s^{-1}) or above (Streten, 1988). Winds of these speeds generate large waves (Dackombe and Gardiner, 1983) of great energy (Davies, 1980). For the last 1 million years or so the belt of sub-tropical high pressure cells has been in its present position over about 30°S, and a westerly circulation has influenced Southern Australia (Bowler, 1982) and the Southern Ocean. To the north of Macquarie Island, in south-eastern Australia, between 18 000 and 16 000 BP major water deficit was accompanied by maximum aeolian activity (Bowler, 1982). To the south, in Antarctica, high particulate concentrations of continental dust derived from mid-lower latitudes are preserved in ice of last glacial maximum age indicating windy, vigorous atmospheric circulation globally and more aridity (De Angelis, Barkov and Petrov, 1987). It is clear that, between 16 000 and 8000 BP, approximately westerly winds no less strong than those of the present produced high energy waves which assailed the west and north coast of Macquarie Island.

Fig. 8. Bedded lacustrine deposits of Palaeolake Skua exposed in cliff at plateau edge about 180m a.s.l. Intermediate width marine terrace borders Sellick Bay on left of photograph.

Swell has strong erosive action where the coast is fronted by a platform shallow enough to steepen the wave form and generate breaking waves very close to or at the shore (Davies, 1980). Cliffs that plunge into deep water do not generate such erosive waves and, at the other extreme, an extremely shallow gently sloping platform causes energy dissipation after the waves have broken offshore. During formation of the Macquarie Island platform, when the sea was eroding the base of the cliffs and steep edges of the plateau, the gently sloping platform was below mean sea-level, and most of its width would have been below the level of effective wave abrasion (King, 1972). Much of the wave energy would have been delivered to erode the base of the cliffs and steep slopes of the western edge of the plateau. With a combination of swell, breaking because of the shelving platform, and storm waves from the presumably still frequent gales, the assailing force of waves on the island must have been high.

The resistance of cliff material to the erosive force of wave action is controlled by its lithology. The mechanical strength of cliff material is reduced by jointing, faulting and weathering (Sunamura, 1983), which are common features of Macquarie Island rocks. Macquarie Island is formed from igneous rocks, intrusive in the northern third, extrusive in the southern two thirds (Duncan and Varne, 1988). Sunamura (1983) compiled over 100 observations of rates of coastal cliff erosion from around the world. Rates ranged from about 1mm to several metres per year, depending on the resistance of the cliff material. Taking into consideration the fractured nature of much of the rock (reducing its resisting force) and the high assailing force of the waves at Macquarie Island, an average rate of coastal cliff erosion of 0.5m per year during the period of rapid sea-level rise between 18 000 and 8000 years ago is quite possible.

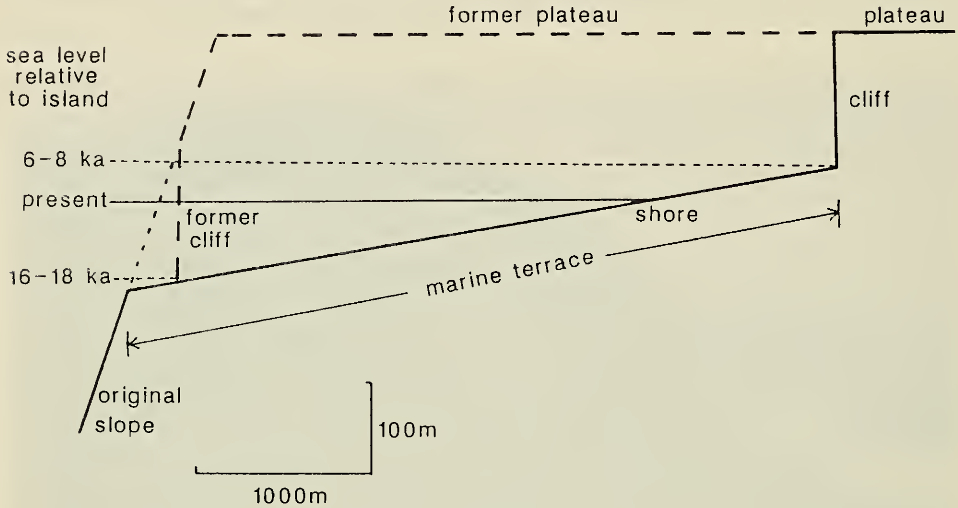

Fig. 9. Diagram to show formation of the wide marine terrace along the north-west coast of Macquarie Island since the last world-wide period of low sea-level about 18 000 years ago (18kA, last glacial maximum). The slope of the marine terrace approximates the minimum slope of a wave-cut rock surface in the Southern Ocean. An arbitrary original slope (probably fault-controlled) is assumed for the western side of the island block. The maximum depth (d) of wave erosion is presumed constant during terrace formation. Sea-level relative to the island is presumed to have changed throughout the last 18 000 years due to known rise in world sea-level (18 000 to 6000 years ago, 18-6kA) and presumed tectonic uplift (18 000 years ago to present, 18-OkA). Sea-level has remained at its present absolute level for about the last 6000 years (6kA). Diagram adapted from Fig. 21.2 of King (1972).

At present on the north-west coast of Macquarie Island, much of the wave energy from the Southern Ocean swell is dissipated offshore on the tectonically emerging gently sloping platform of bedrock and boulders so that wave action on the present shoreline is reduced relative to when the platform was being formed.

The west-north-west dominant orientation of wind, and the half-heart shape of Bauer Bay between Douglas Point and Mawson Point ensure that sand, carried down into shallow Bauer Bay by two major creeks from the plateau, will remain largely trapped there (Fig. 3). The orientation of shore and wind is also favourable for long-shore movement of sand at least south of Douglas Point. The extensive sand deposits at between 100 and 200m above present sea-level on the plateau above Bauer Bay (Adamson, Selkirk and Colhoun, 1988) suggest that sand has been trapped in former equivalents of the present bay during uplift of the island. The cobbled beach (Beach 5 of Ledingham and Peterson, 1984) is presumed to be approximately coeval.

The marine terrace, especially around the north-west coast, seems to be an unusually wide example of a Type A platform (King, 1972) with a gentle slope seaward, and little or no scarp formed by present wave action. The ultimate seaward scarp of this platform at about 70-100m below present sea-level was probably controlled by faulting and the lowest level reached by the sea at last glacial maximum time, c.18 000 BP. In Scotland raised coastal platforms and fossil sea cliffs of similar morphology have been formed by isostatic uplift after ice retreat (Steers, 1973).

The width of the marine terrace on the north-west coast far exceeds that formed by tidal action on a stable coast. By invoking the global rise in sea-level after the terminal Pleistocene glacial period, the extraordinary force of the Southern Ocean, the fractured nature of the rock, and an appropriate depth of water offshore, the width of the terrace can be explained. Tectonic uplift of the island probably occurred throughout the period of global sea-level rise. Continuing tectonic uplift of the island explains the present emergence of the landward portion of the terrace.

Differential tectonic movement of fault-bounded blocks, tilting of blocks, and more vigorous wave attack on the west coast may explain the great differences in width of emergent marine terraces around the coast (Fig. 1). The narrow or non-existent terrace along the east coast, in contrast to the wide western terrace, may be due to slight tilting of the northern half of the island downwards to the east. A shallow underwater platform is present off the east coast (Fig. 6).

The model originally proposed for the formation of the Macquarie Island marine terrace on the north-west coast (Adamson, Selkirk and Colhoun, 1988) is supported by bathymetric measurements. An assumed 8000 years of vigorous terrace formation (16 000 to 8000 years ago) has cut a terrace of total width 3700m and 2° slope (mean of 5 measured traverses). The landward edge of the terrace is estimated now to be at an altitude of 15 to 20m. Assuming this to have been raised from sea-level by tectonic activity during the past 6000 years of stable sea-level yields a calculated uplift rate of approximately 3mm per year. This value accords well with the independent estimates of Colhoun and Goede (1973), Bergstrom (1985) and Selkirk, Seppelt and Selkirk (1990) for the northern portion of the island between Green Gorge and the Isthmus.

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